III. Advanced Engineering: Communications System Research

A. Radar Observations of Icarus, *R. M. Goldstein*

1. Introduction

Bistatic radar observations of the asteroid Icarus were made on June 14, 1968, when its orbit came within four million miles of earth. Icarus comes this close to earth only once in 19 years, and this recent approach was the first opportunity for radar study. RF spectral measurements of the echoes provide data dependent on the size, shape, spin, velocity, and radar cross section of the target. It is estimated that the radius is between 0.3 and 0.6 km and the rotation period is between 1.5 and 3.3 h.

Icarus is an extremely difficult radar target. Its radar detectability is only 10^{-3} times that of Mercury (at closest approach) and 10^{-12} that of the moon. Only the most powerful and sensitive radars of modern technology can detect Icarus.

2. Experiment

This experiment demonstrated the capability of the new 450-kW transmitter on the Venus DSS 85-ft antenna, combined with the 210-ft antenna at the Mars DSS as the receiving antenna. The Mars DSS is approximately 14 mi away from the transmitter. Because of this separation, it was possible to transmit and receive simultaneously most of the time. However, when the elevation angle was low, or during the several hours of closest approach when the doppler went through zero, it was necessary to transmit and receive in alternate cycles. Each cycle lasted 43 s, the round-trip time of transmission.

The radar station parameters for this experiment are as follows:

Power	450 kW
Frequency	2388 MHz
Two-way antenna gain	116.0 dB
System temperature	21°K

Pure monochromatic waves were beamed at Icarus. The frequency spectrum of the weak echoes was measured at the receiver, using correlation techniques. Any rotation that Icarus might have would broaden the spectrum of the echo and leave a characteristic pattern.

Three functions of the radar were controlled by ephemerides:[1] pointing of the 85-ft antenna, pointing of

[1]Recent accurate ephemerides provided by G. Null and D. Holdridge of JPL and S. Herrick of UCLA; critical optical observation of Icarus supplied by E. Roemer, University of Arizona.

the 210-ft antenna, and tuning of the receiver to account for the relative velocities of Icarus and the tracking station.

Ordinarily, receiver runs of 30 min were made, and the resulting spectrum was displayed. Because of the unusually low power level of the echo, none of these runs produced a clear detection of Icarus. Although there were indications of an echo, they were obscured by the random fluctuations of the spectra.

3. Measurements

When 4 h of data were averaged, however, the result was not only positive detection of Icarus, but also an indication of power, bandwidth, and center frequency. Altogether seven such average spectra were taken. They are reproduced in Fig. 1. Each is the result of 3 to 4 h of averaging.

The radar was calibrated by directing it at the planet Mercury, leaving everything unchanged except for the three ephemerides. Figure 2 is a sample result of averaging 9 min of echoes from Mercury. Note the different scale in frequency.

The total received power is obtained from the area under each spectrum. An average echo power of 0.63×10^{-22} W was obtained from Icarus. When the radar parameters of range, antenna gain, etc., are taken into account, the result is the radar cross section σ. For Icarus,

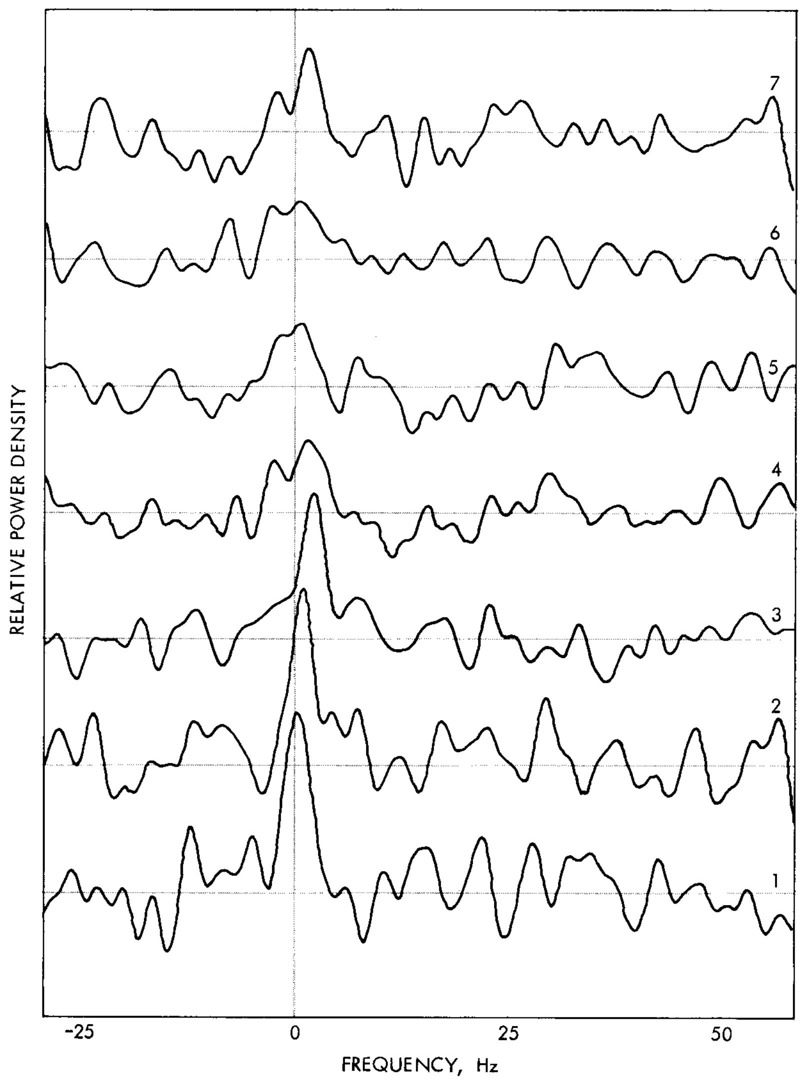

Fig. 1. Individual spectra of Icarus echo

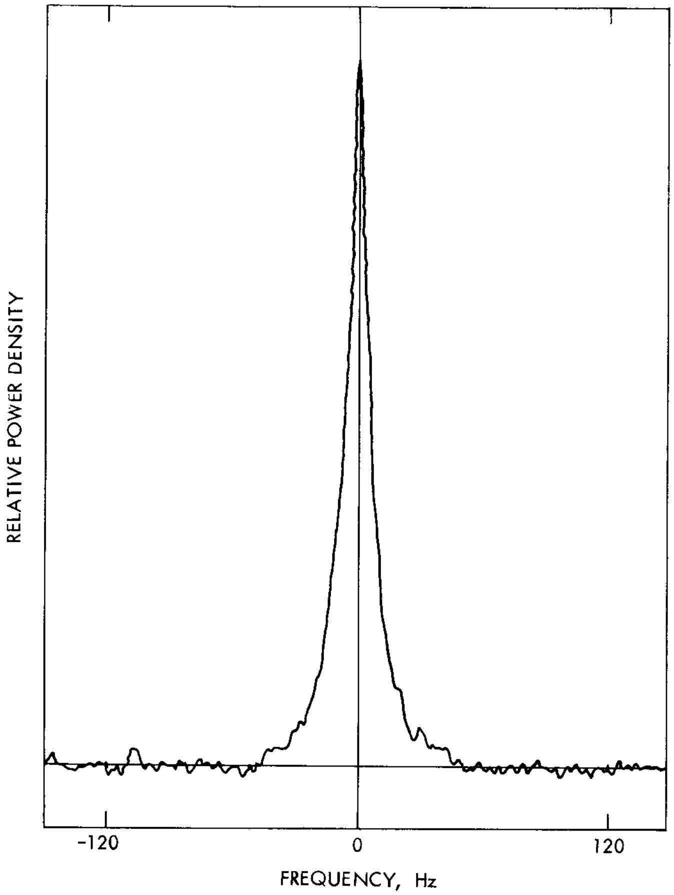

Fig. 2. A sample spectrum of an echo from Mercury, used to calibrate the radar

the result of the experiment is

$$\sigma = 0.1\ \text{km}^2$$

Radar cross section is defined as the effective cross-sectional area of the target. Two factors, reflectivity and directivity, are multiplied onto the actual area. In order to estimate the target radius, it is necessary to assume a reflection model. Radii of Icarus have been computed under the assumption that Icarus reflects in the same way as either Mercury, moon, or Venus. The results are shown in Table 1.

Table 1. Radius and rotation period of Icarus

Reflection model	Radius, km	Rotation period, h
Mercury	0.6	0.7
Venus	0.5	0.5
Moon	0.7	0.9
Rough, metallic	0.3	1.5
Rough, stony	0.6	3.3

The bandwidth B of the spectra at the half power points are related to the spin rate of Icarus by

$$B = \omega r / Q$$

where ω is the effective spin rate, r is the radius, and Q is an unknown shape factor of the spectrum which depends on the roughness of the target. For Mercury, Q equals 7.4.

Once again one has to assume a reflection model in order to compute the spin rate. The rotation period has been estimated for the same models as before, and these results are also listed in Table 1. The effective spin rate is the projection of the actual one, across the line of sight. There is, in addition, a small orbital component of effective spin, but for Icarus this component is negligible.

The 4-h average spectra of Fig. 1 are very noisy and inconclusive. However, a trend does appear in these records. The first two show a single frequency of maximum response, whereas the last four appear bimodal. The third spectrum appears to be transitional. Figure 3 is the result of averaging the last five spectra, so that the bimodal structure shows up clearly. This spectrum has twice the frequency resolution of Fig. 1.

This change cannot be interpreted as the result of Icarus' rotation, since each spectrum is the result of almost 4 h (hence more than one period) of averaging. However, the subradar point on Icarus moved appreciably during the 2½ days of the experiment. Figure 4 shows this motion, with the position at the time of each spectrum marked.

If Icarus is rough, even jagged, and not necessarily round, the spectrum would be expected to change with the motion of the subradar point. In particular, the slow change from unimodal to bimodal can be explained in terms of the motion of the subradar point and the supposed irregular shape of Icarus.

Consequently the radius and spin are computed for two additional models of reflectivity: rough and metallic and rough and stony. The rough assumption leads to a Q factor of $2^{1/2}$. Reasonable reflectivities for metallic and stony surfaces are 0.5 and 0.1, respectively. The corresponding values of the radius and rotation period are listed in Table 1.

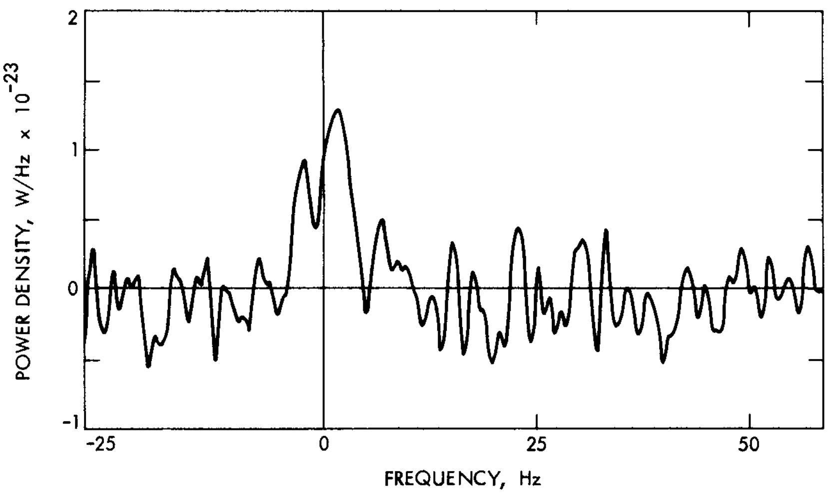

Fig. 3. Icarus 17-h average spectrum

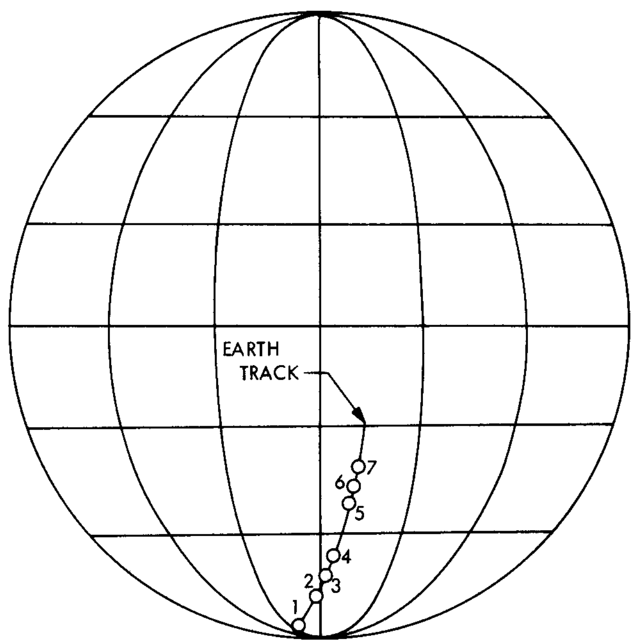

Fig. 4. Position of subradar point on Icarus, assuming no rotation

The center frequency of each spectrum gives the doppler shift and, hence, the line of sight velocity of Icarus. Because of the irregular shape of the spectra, the center frequency is imperfectly determined. We have chosen the "center of gravity" of the spectra as our estimate of the center. The resulting doppler measurements are given in Table 2. This data can be used to improve the ephemeris of Icarus.

Table 2. Doppler measurements of Icarus

Spectrum	Received time		Doppler, Hz
	Day (1968)	h:min	
1	166	05:30	+ 115417.1 ±0.3
2	166	22:20	− 10324.1
3	167	04:30	− 61207.2
4	167	09:40	− 104441.9
5	168	01:40	− 202453.5
6	168	06:30	− 234710.0
7	168	10:00	− 255404.7

B. Simulation of the Programmed Oscillator for Laboratory Testing of Control Programs,

R. F. Emerson

1. Introduction

The Mod V programmed oscillator (PO) is a complex subsystem and its control program is even more complex (SPS 37-39, Vol. III, pp. 71–76). By simulating the programmed oscillator with software, new programs may be tested without tying up an entire tracking station.

2. Method

The simulation program consists of three basic parts: the initialization or setup, the interrupt simulation, and the device simulation routines. The setup routine connects the two programs so that they may operate as one (Fig. 5a). The connection of the two programs is done by replacing the device EOM, EOM-POT, and EOM-PIN